VIPR: Vapor In-Cloud Profiling Radar (IIP-16)

ESTF June 11-13, 2019
Mountain View, CA

Presented By: Raquel Rodriguez-Monje

Coauthors: Matt Lebsock, Ken Cooper, Ricky Roy, Jose Siles, Luis Millan, Bob Dengler

Problem Statement

Problem

- Existing remote sensing platforms have limited ability to retrieve *high-resolution, unbiased* water vapor profiles in the presence of clouds

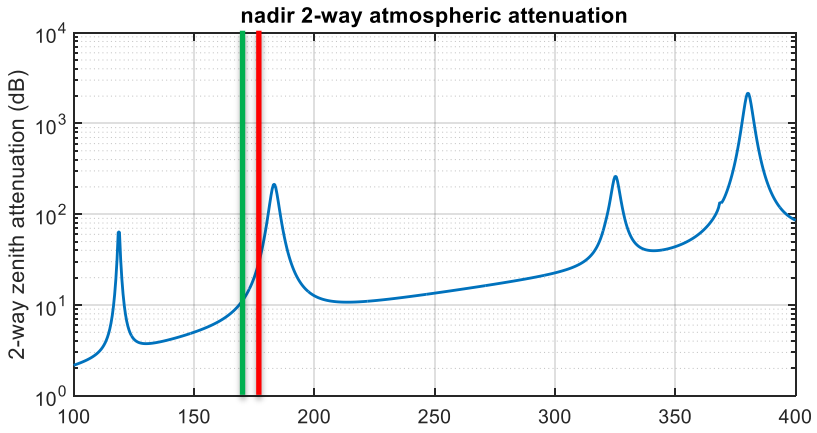
- Problem recognized by NWP community (WMO, 2018):
  "Critical atmospheric variables that are **not adequately measured** by current or planned systems are temperature and **humidity profiles** of adequate vertical resolution **in cloudy areas**."

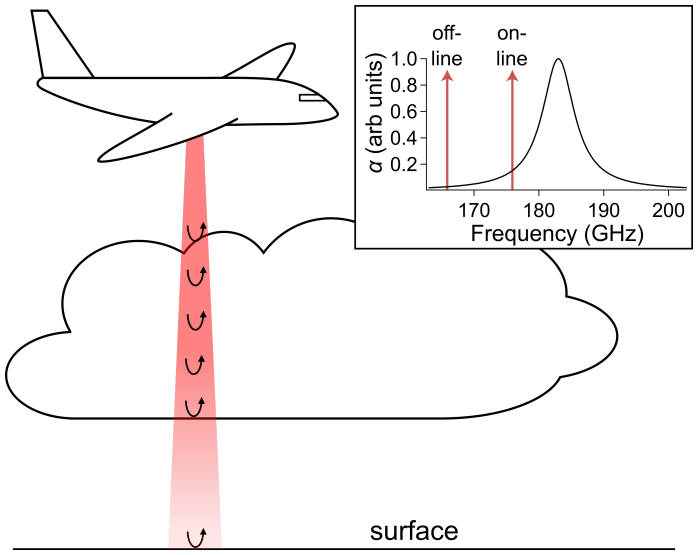
Proposed Solution

- Utilize range-resolved radar signal *and*frequency-dependent attenuation on flank of 183 GHz water vapor absorption line, so-called *differential absorption radar* (DAR)

- Microwave analog of differential absorption lidar(DIAL) –but can measure inside clouds

Measurement Basis





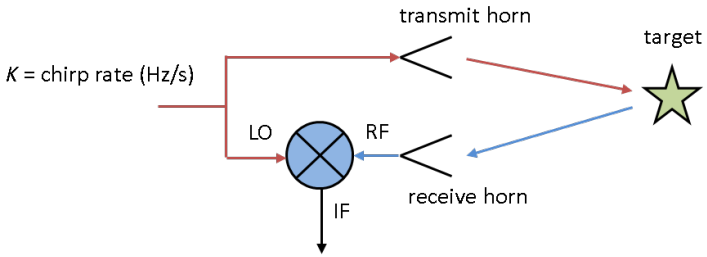
- Differential reflectivity between two closely spaced frequencies proportional to water vapor density
- *Key Assumption*: Reflectivity and extinction from cloud liquid is independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Radar provides range resolution / Differential technique is self-calibration

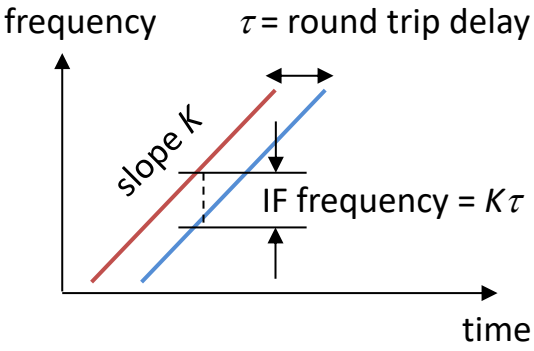
Connection to Decadal Survey

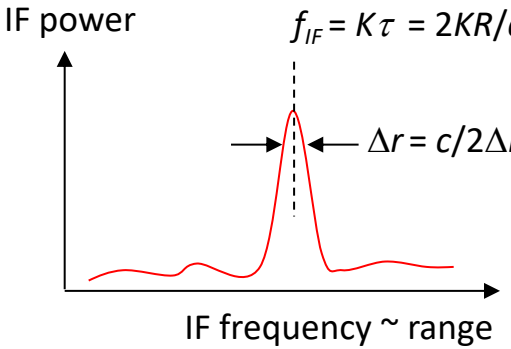
TARGETED OBSERVABLE	SCIENCE/APPLICATIONS SUMMARY	CANDIDATE MEASUREMENT APPROACH	Designated	Explorer	Incubation
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights.	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			X

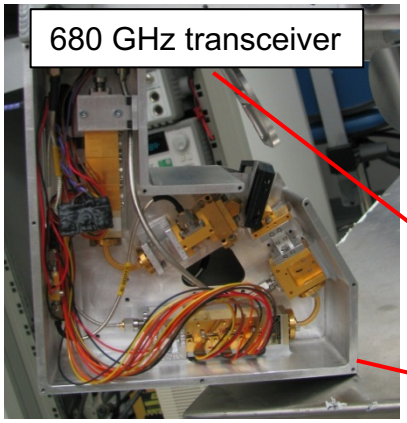
VIPR addresses the measurement needs for the Planetary Boundary Layer (PBL) incubation area by providing high vertical resolution water vapor profiles within PBL clouds and precipitation

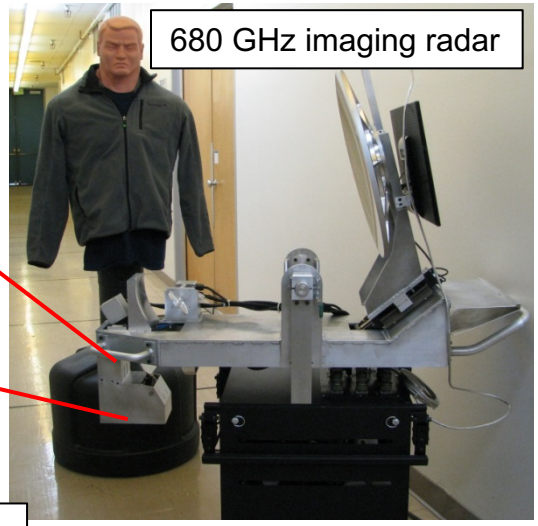
Measurement Approach

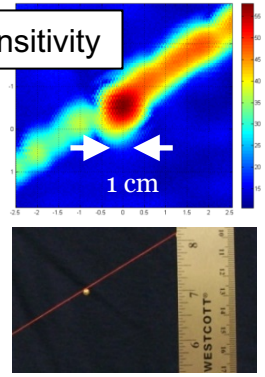






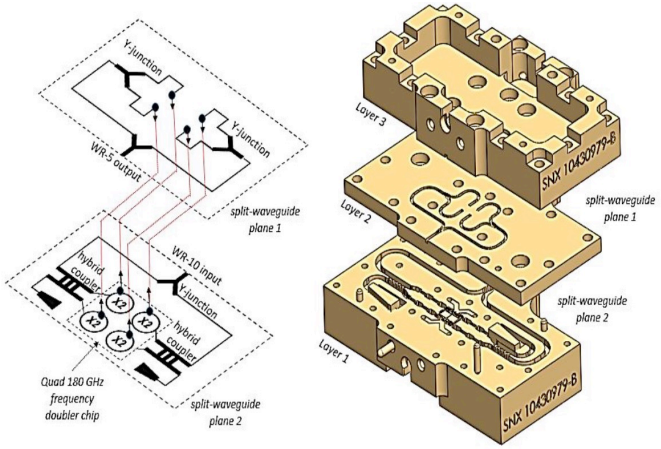


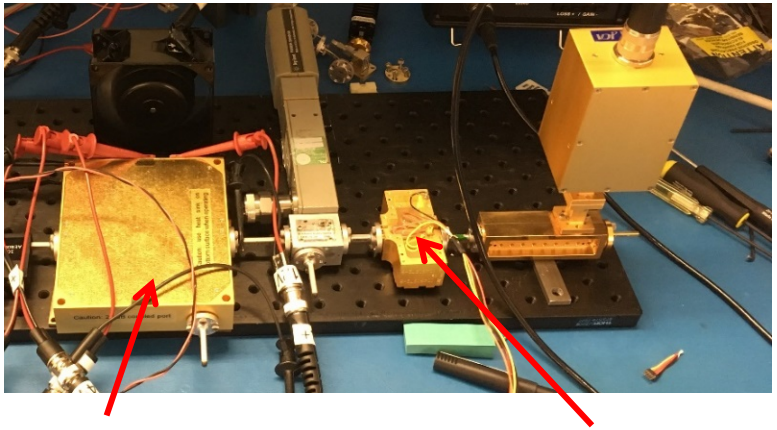




Key Technologies

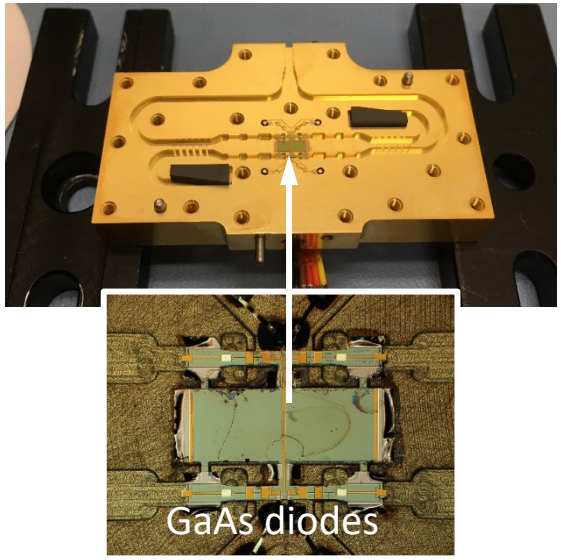
Power-combined (4x) frequency multiplier (2x) technology at JPL

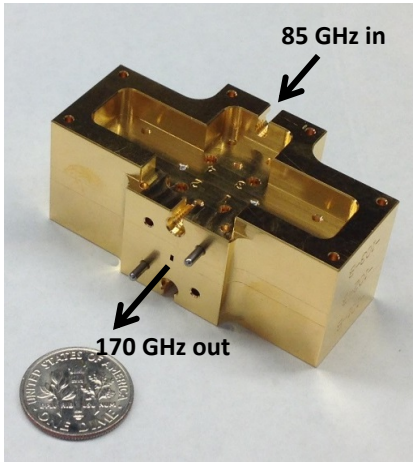


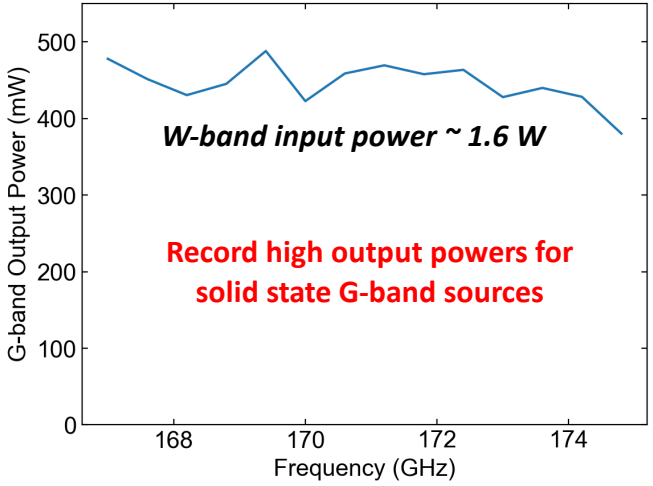


Millitech power-combined W-band PA module with 85 GHz Raytheon GaN MMICs

G-band quad doubler



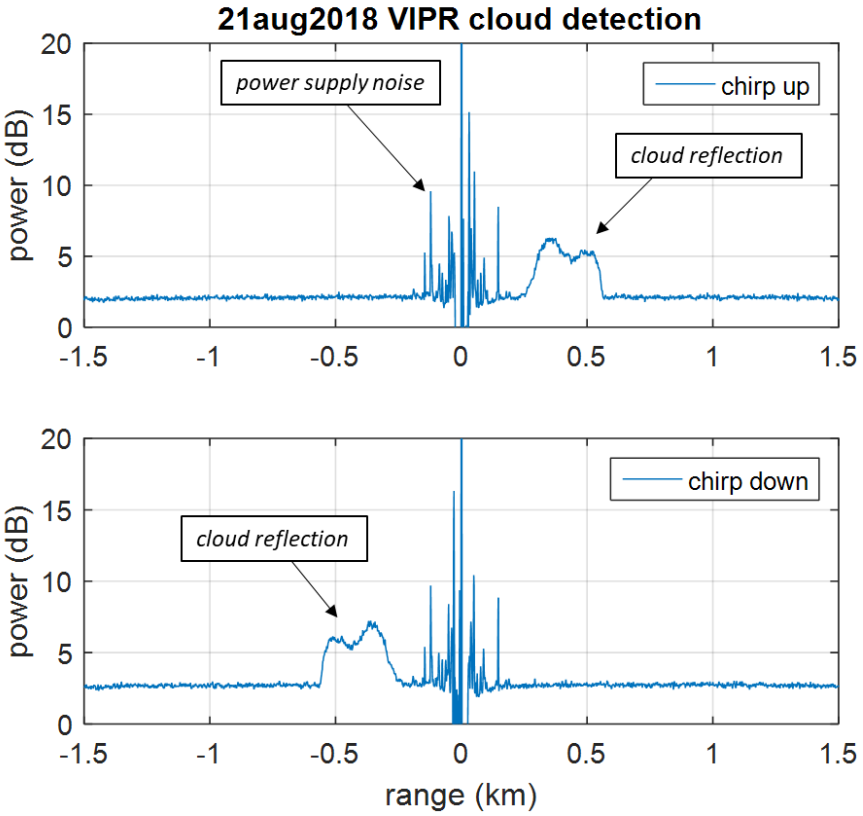


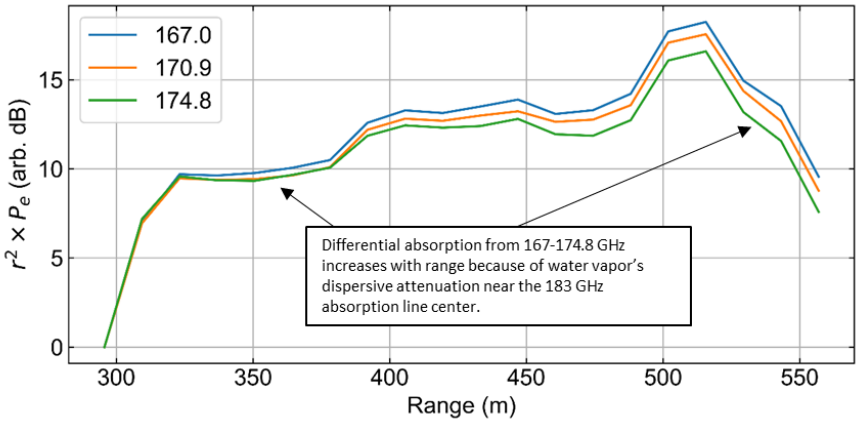


Jose Siles *et al., IEEE Transactions on Terahertz Science and Technology*, vol. 8, no. 6, pp. 596-604, Nov. 2018.

First Full-VIPR Detections of Clouds and Humidity

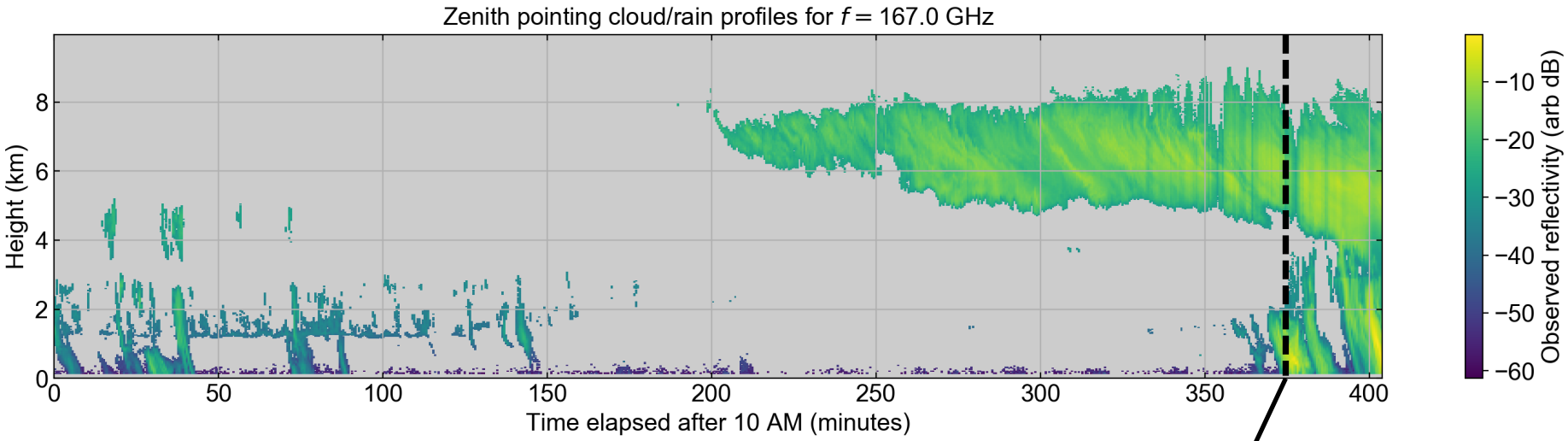
A mix of very light and thicker morning low clouds were present early in the morning of 8/21/2018.

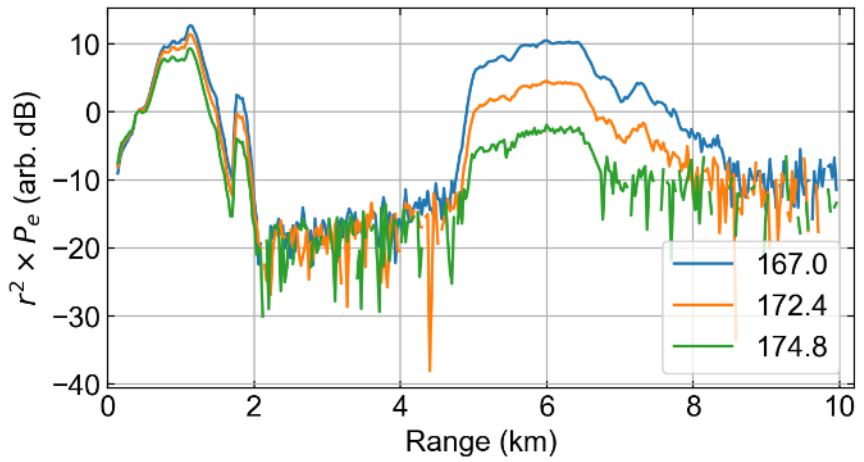




First Full-VIPR Detections of Clouds and Humidity

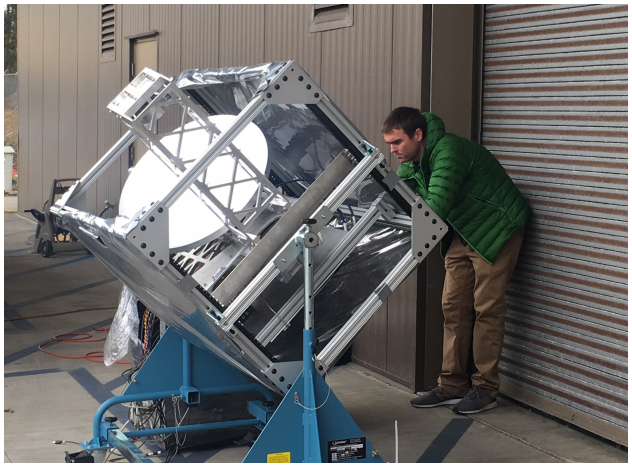
October 3, 2018 @ JPL – Clouds detected beyond 8 km in height

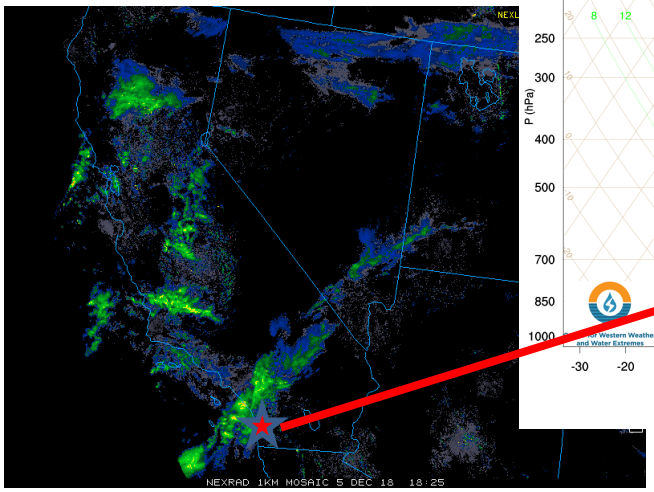


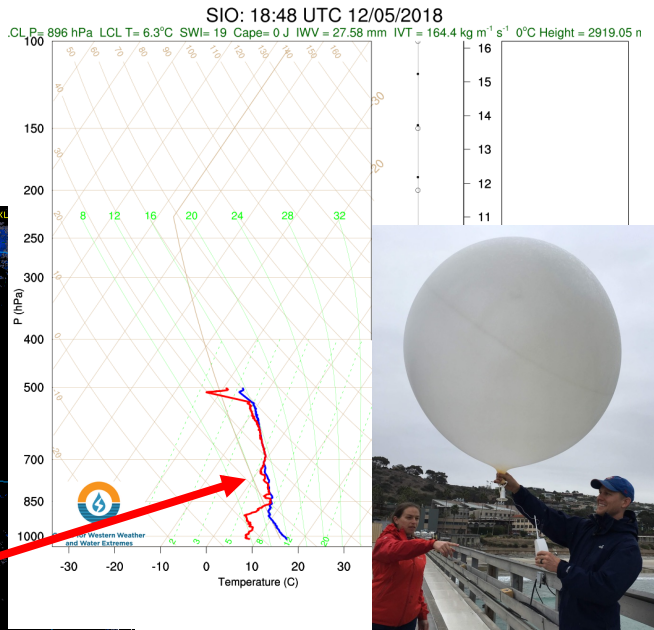


Scripps Field Testing and Radiosonde Validation

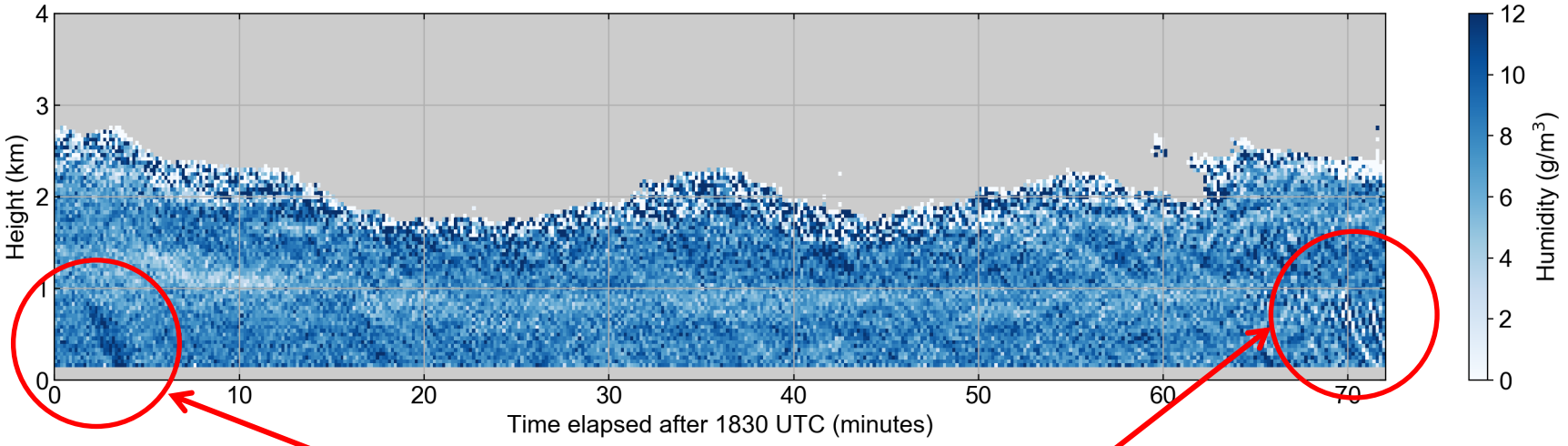
- Scripps validation deployment (12/5/2018) in collaboration with the Center for Western Weather and Water Extremes
- VIPR Observed 6 hours of a cold-frontal passage
- Scripps CW3E Launched 8 radiosondes



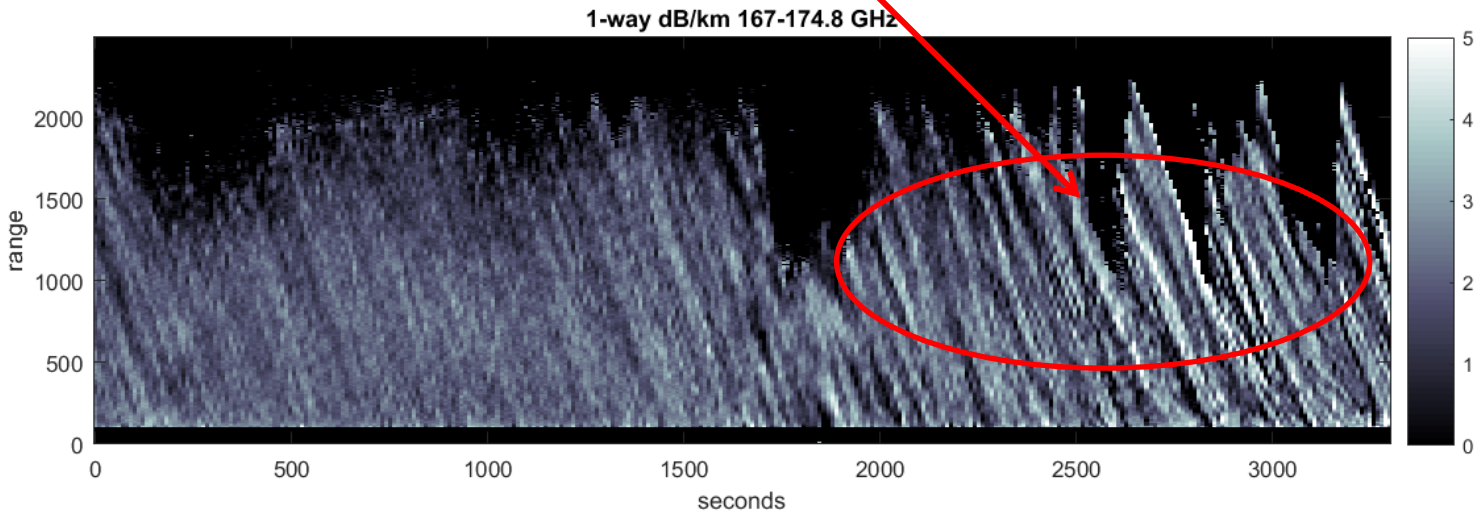




Humidity Variance and Biases



What causes these variations?



Understanding and Mitigating Biases

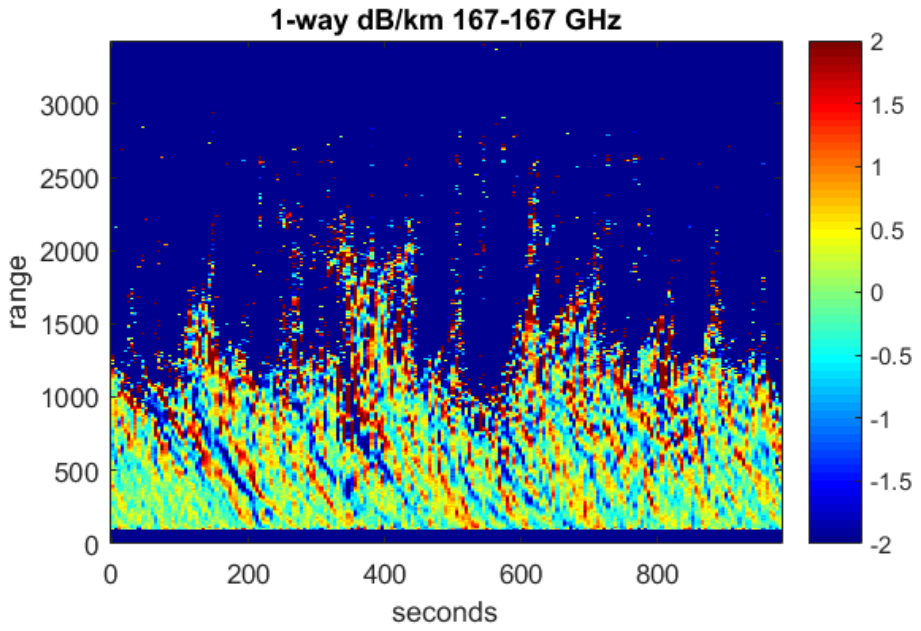
Problem: High spatial frequency oscillations in the derived humidity are observed when the scene is transient.

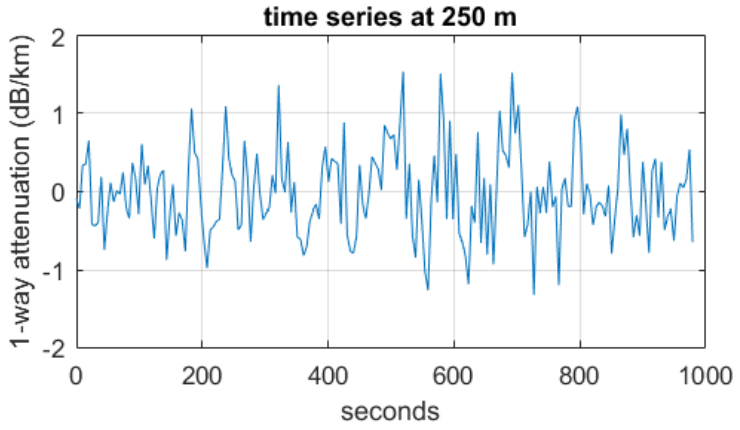
Experiment: Derive the differential attenuation between between 167 and 167 GHz

- It should be 0 but streaking and excessive bias is still seen even when not switching frequencies!

The Causes:

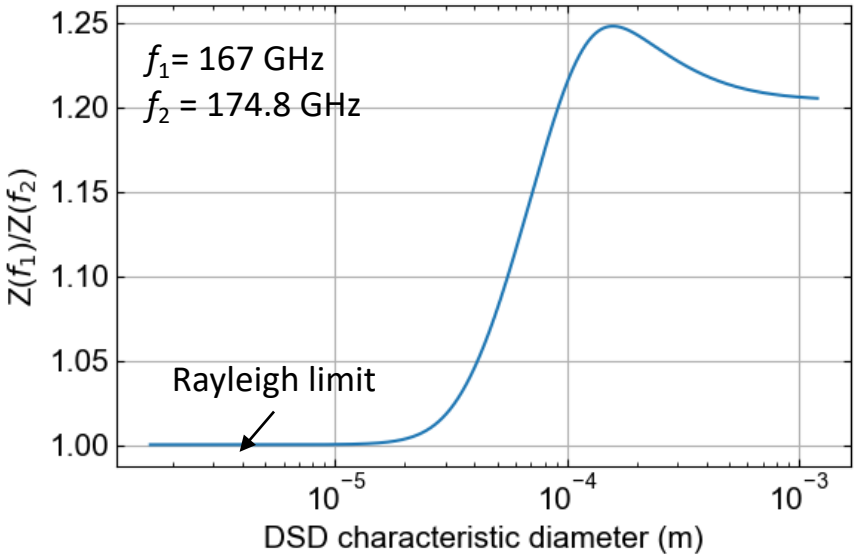
1. Frequency switching was too slow
   - 400 ms reduced to 10 ms eliminates the problem.
2. The drop size distribution changes rapidly in space violating algorithm assumptions
   - Can be mitigated with additional frequency measured at 158 GHz but not possible with current hardware.





New Retrieval: Regularized Least Squares

- **Problem:** biases from frequency dependence of hydrometeor scattering
- Limit biases by:
  1. Averaging profiles over 10 minutes to smooth out drop size distribution (DSD) heterogeneity
  2. Use new retrieval algorithm to include systematic uncertainty and penalize unphysical gradients of humidity



Retrieval methodology

- Minimizes the difference between observations [y] and our physical model [F(x,b)]
- The minimization is weighted by both measurement error and systematic error caused by unknowns (b).
- The humidity gradient term effectively provides vertical smoothing by punishing high frequency variability in the retrieved humidity

Measurement error

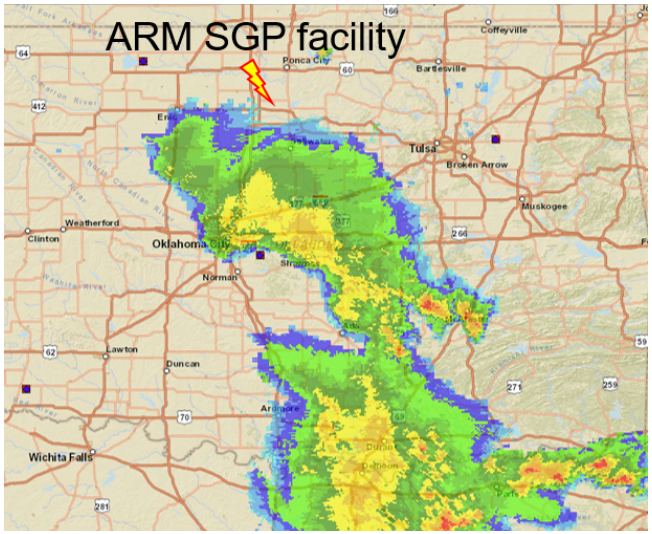
$$\mathcal{C}(\mathbf{x}) = (\mathbf{y}-\mathbf{F}(\mathbf{x},\mathbf{b}))^T(\mathbf{S}_y+\mathbf{S}_e)^{-1}(\mathbf{y}-\mathbf{F}(\mathbf{x},\mathbf{b}))$$

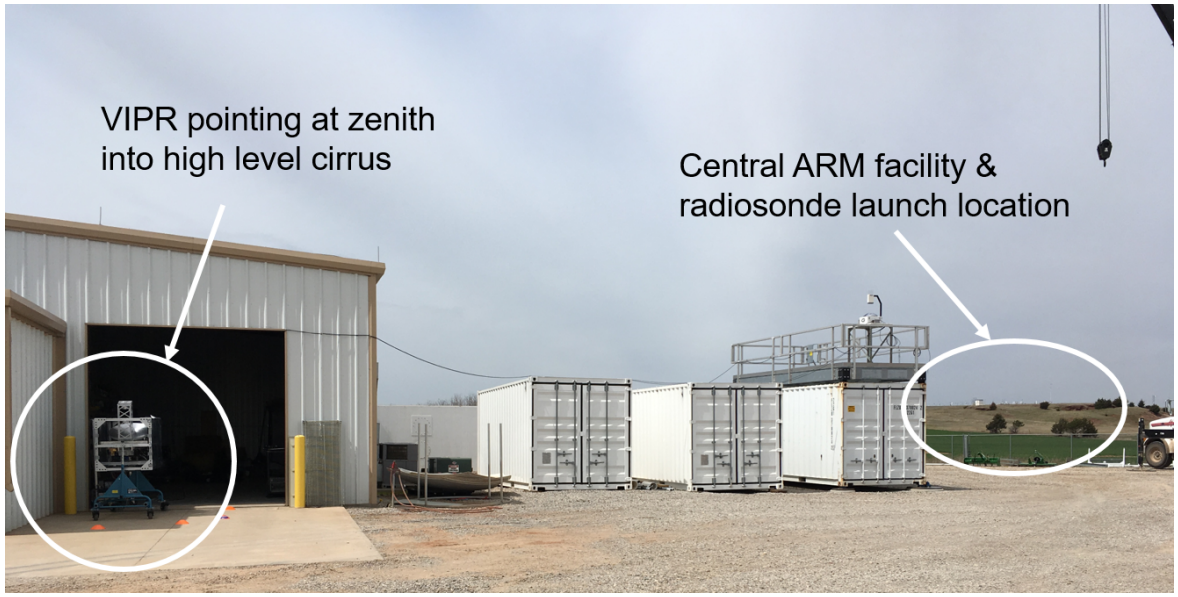
Systematic uncertainty

$$+\delta^{-2}\mathbf{x}^T\mathbf{A}\mathbf{x}$$

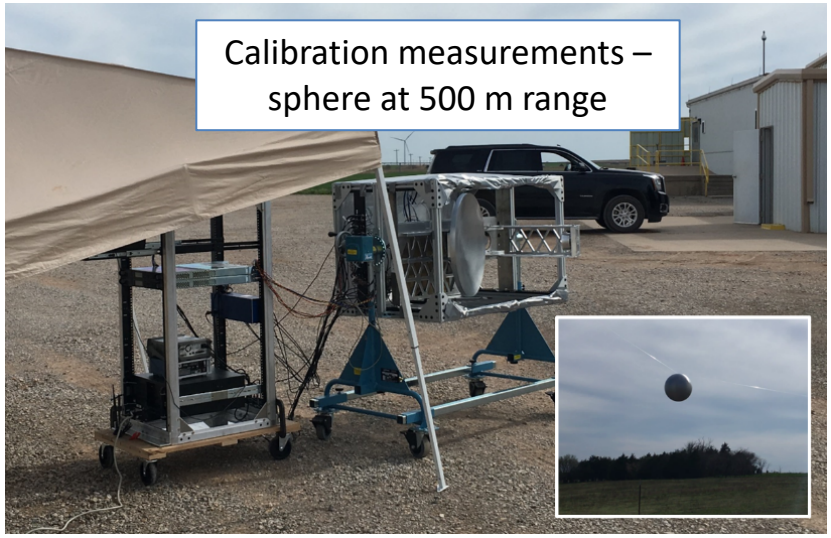
Humidity gradient penalty term

Deployment at ARM SGP site

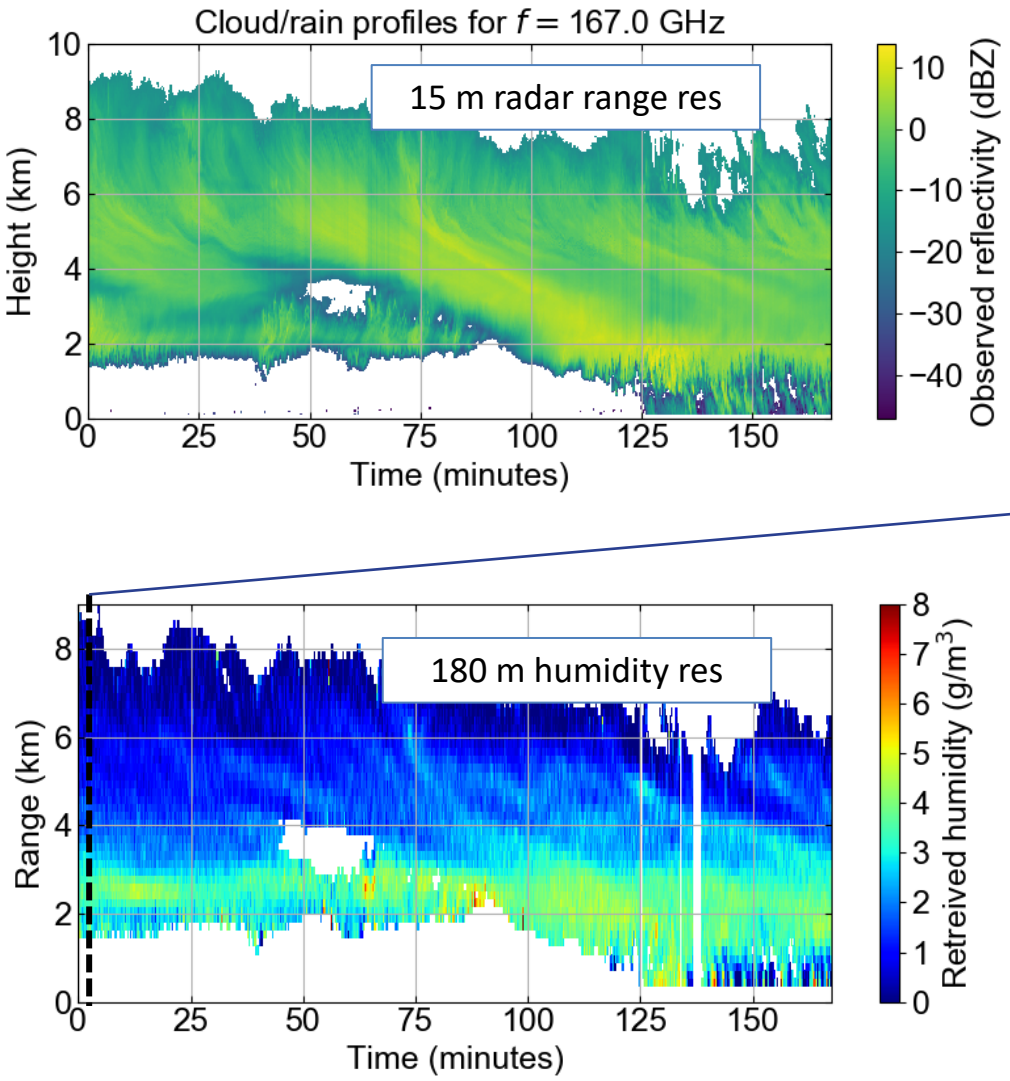




- VIPR deployed from April 2-14, 2019
- Multiple convective systems passed through during the intensive observation period
- Performed radar calibration with high-sphericity calibration targets
- 4x daily radiosonde launches at ARM – supplemented with JPL supplied sondes (launched at will)
- Additional ARM humidity measurements include Raman lidar, passive microwave and infrared

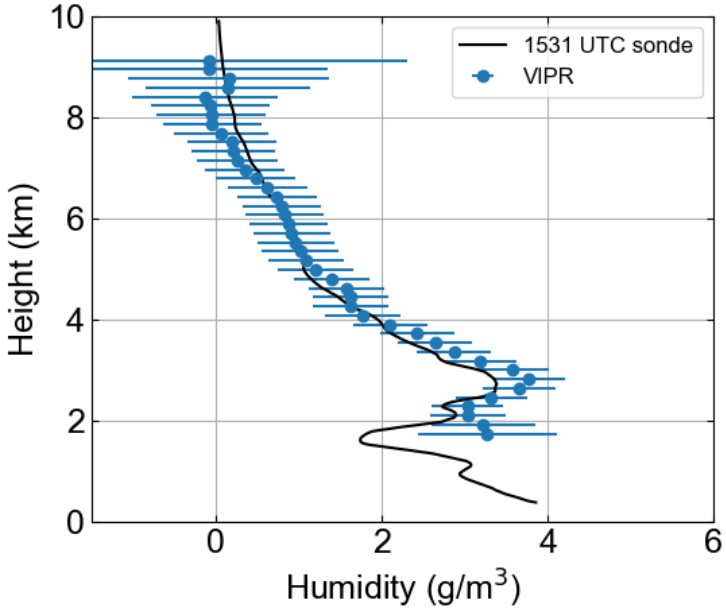


In-cloud Profile Validation

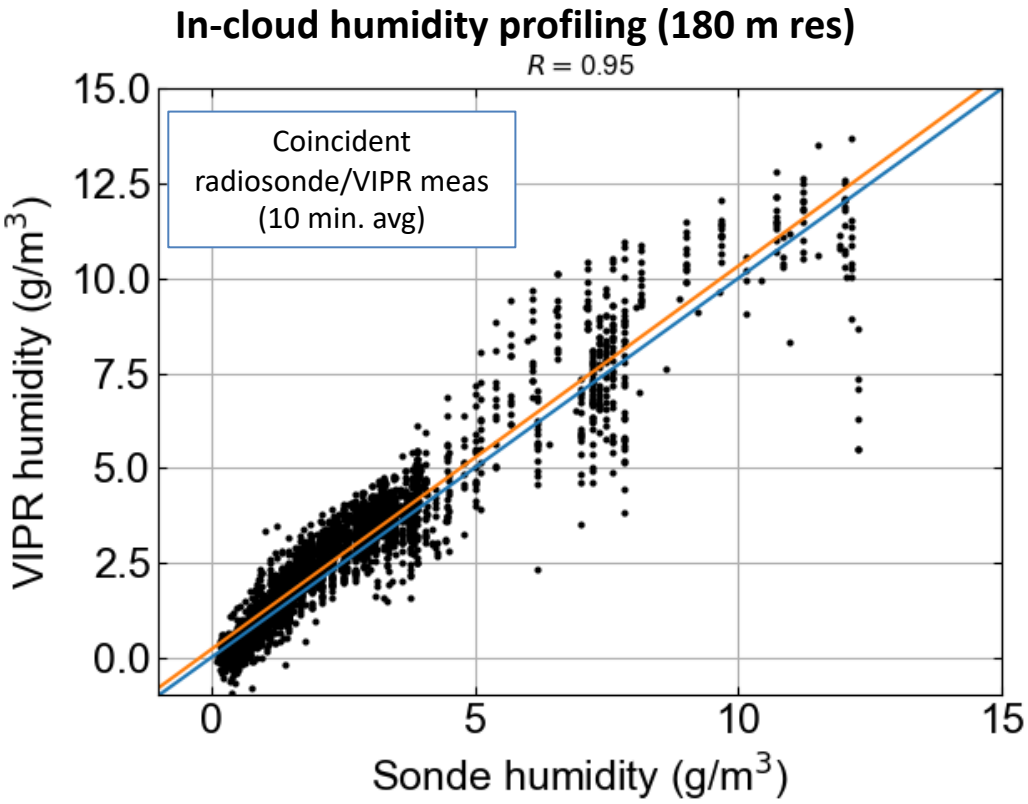


April 13, 2019

VIPR/radiosonde comparison using 10 minute average of DAR humidity



Validation: Summary Statistics



Summary of comparison with 21 radiosondes over 2-week deployment

- Correlation = 0.96 with minimal bias.
- Retrieved water vapor content over 2 orders of magnitude.

Concept for VIPR Twin Otter Deployment

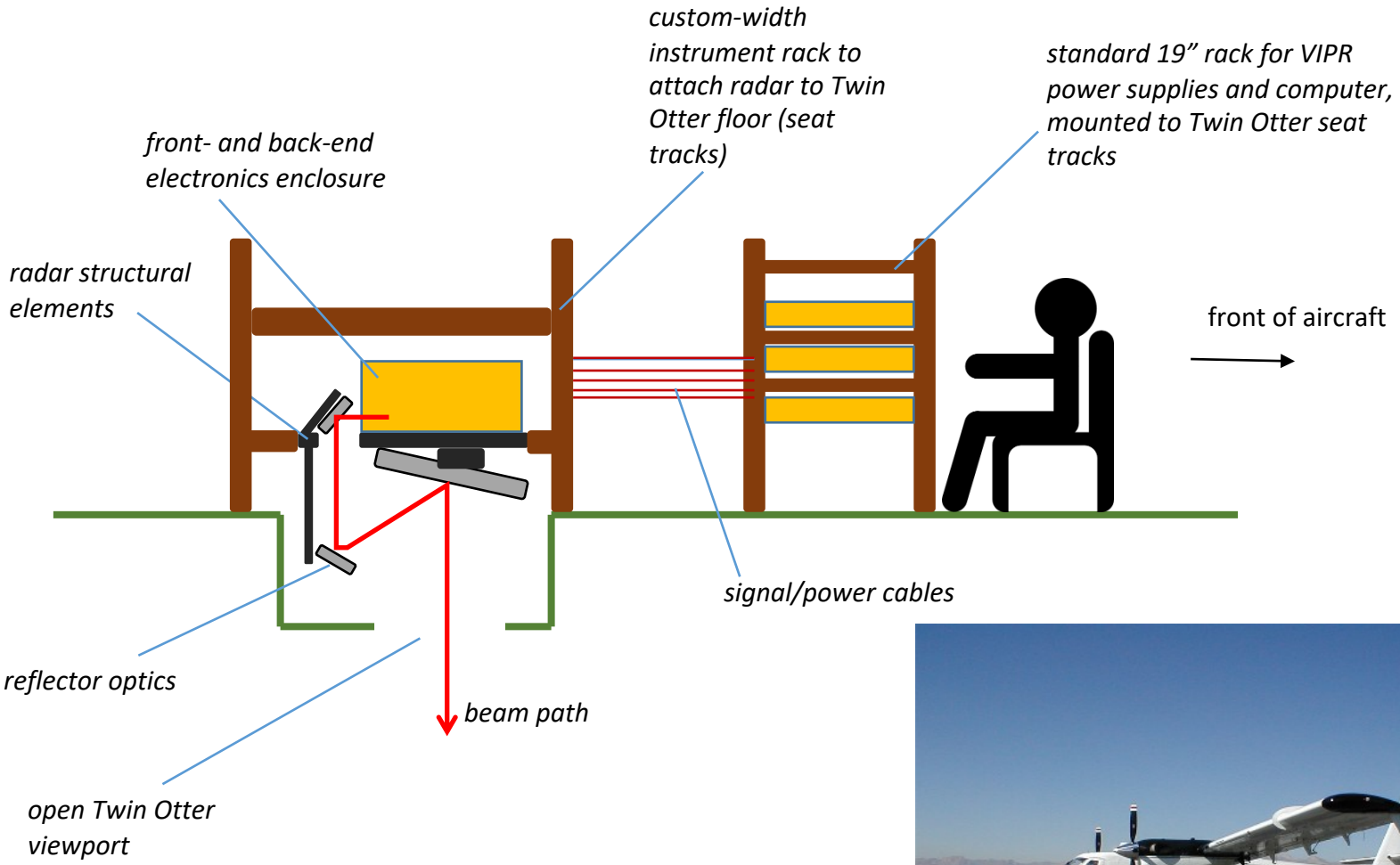
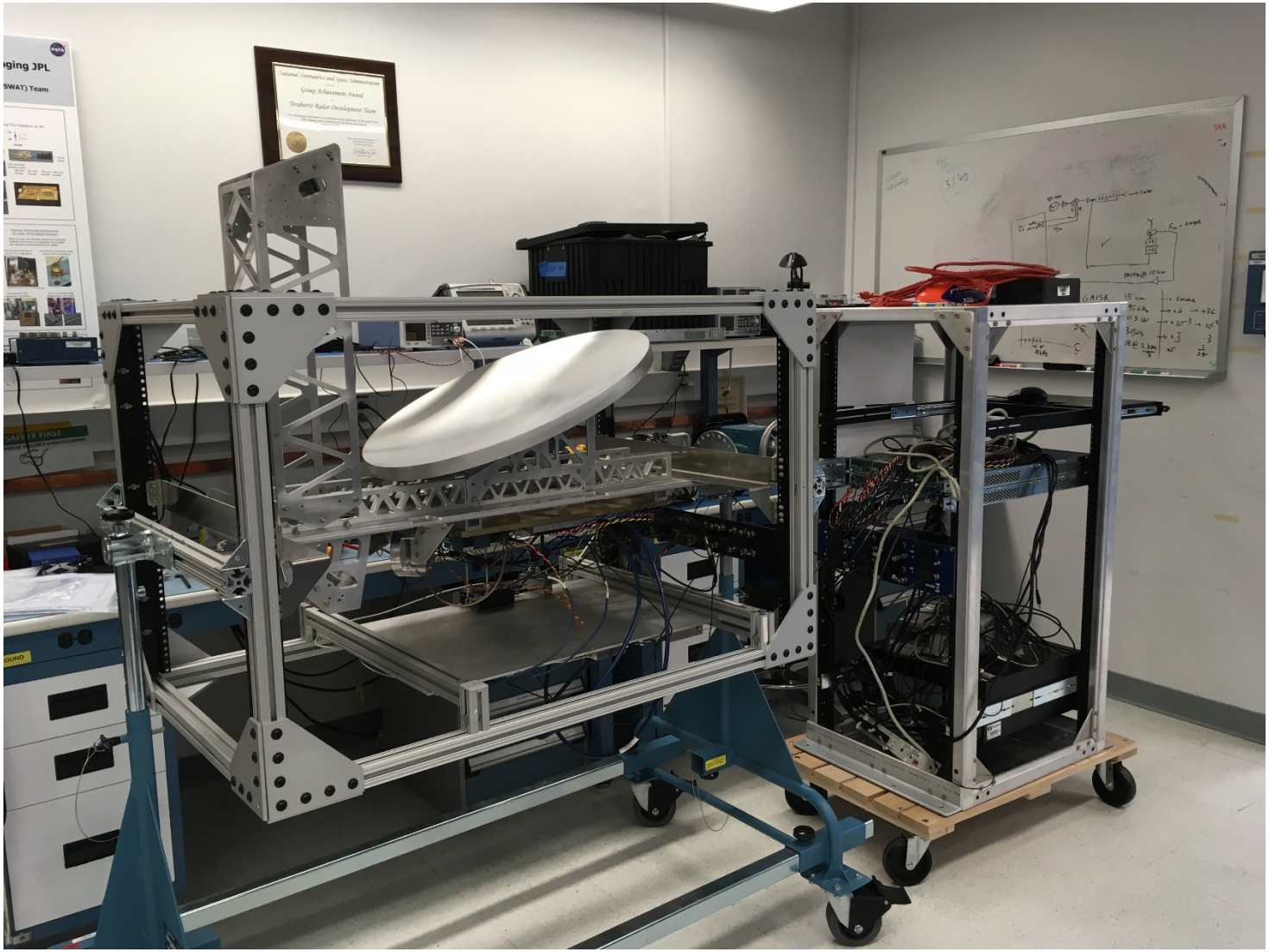
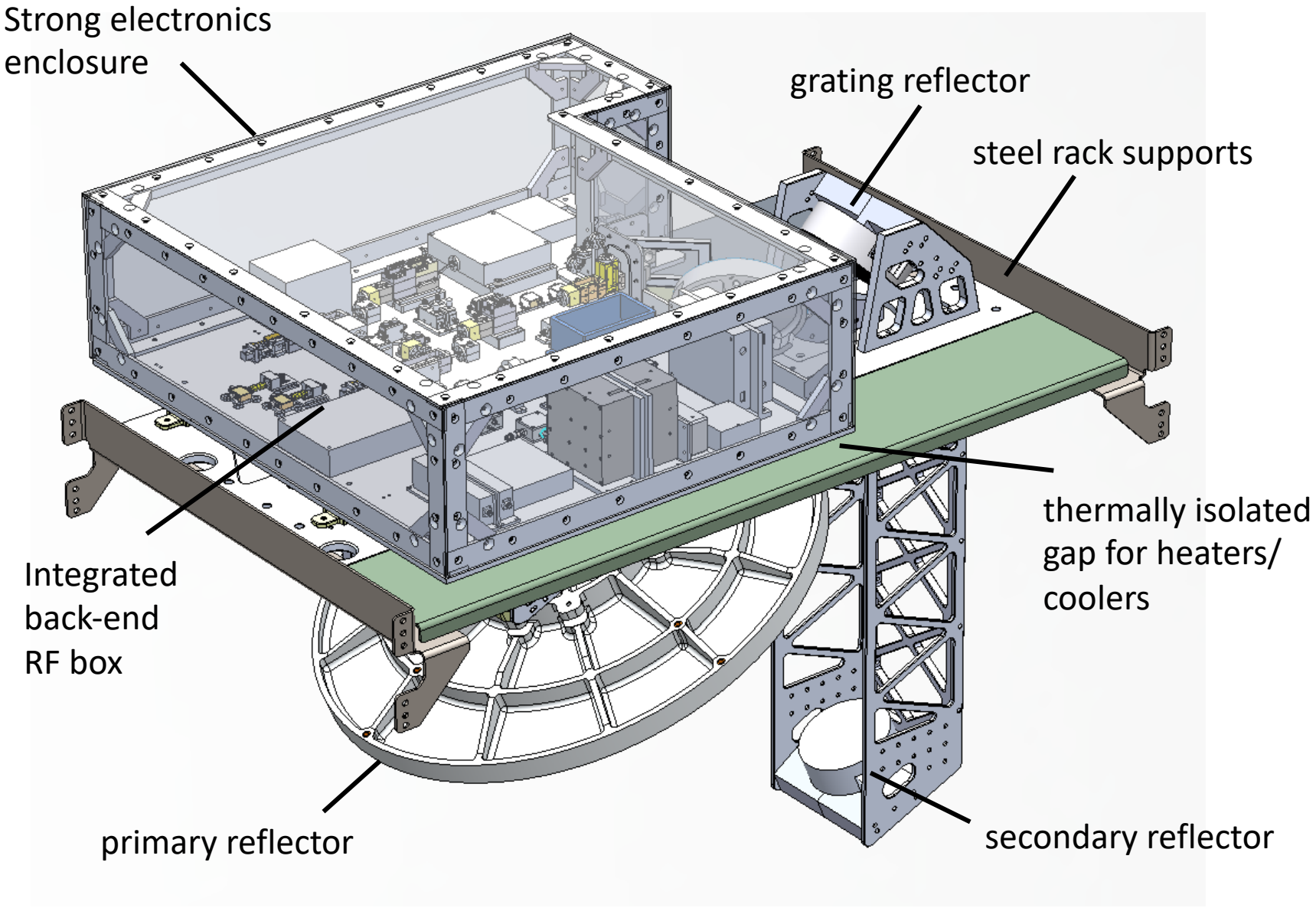


Photo of Current VIPR Hardware



Airborne VIPR Mechanical Design



Next Steps

- Airborne demonstration flights planned for October 2019 in the Pacific Northwest -> TRL-6.

- Work towards testing an additional frequency at 158 GHz to mitigate retrieval biases caused by frequency dependent backscattering.

- Moving forward there will be a real need to fly VIPR with a suite of other PBL sounders (e.g. DIAL) and dropsondes to characterize the relative strengths and weaknesses of each measurement approach.